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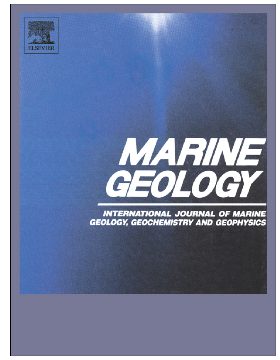

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Intense hurricane transports sand onshore: Example from the Pliocene Malbusca section on Santa Maria Island (Azores, Portugal)

Markes E. Johnson[a], Alfred Uchman[b], Pedro J.M. Costa[c], Ricardo S. Ramalho[cde], and Sérgio P. Ávila[fghi]

[a] Department of Geosciences, Williams College, Williamstown, MA 01267 USA

[b] Institute of Geological Sciences, Jagiellonian University, Oleandry 2a; PL 30-063 Kraków, Poland

[c] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

[d] School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol, BS8 1RJ, UK

[e] Lamont-Doherty Earth Observatory at Columbia University, Comer Geochemistry Building, PO Box 1000, Palisades, NY 10964-8000, USA

[f] Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, Porto, Portugal

[g] CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Pólo dos Açores, Portugal

[h] Departamento de Biologia, Universidade do Açores, 9501-801 Ponta Delgada, Açores, Portugal

[i] MPB-Marine PalaeoBiogeography Working Group of the University of the Azores, Rua da Mãe de Deus, Portugal 9501-801

Corresponding author: Markes E. Johnson (markes.e.johnson@williams.edu)

ABSTRACT

Southern cliffs on Santa Maria Island in the Azores archipelago (North Atlantic Ocean) feature submarine volcanic sequences inter-bedded with Pliocene coralline algal limestone, shelly coquinas, and mixed volcaniclastic-calcarenite sandstone. Within the 20-m sedimentary succession at Malbusca, a singular, 5-m sandstone bed is distinguished by dark and light laminae dominated alternately by heavy minerals and carbonate detritus. Carbonate grain-size varies between that of coarse silt and very fine sand. The basal part shows coarser and more poorly sorted sand in an upward transition to increasingly finer carbonates. Accessible over a lateral space of 34 m, the big bed is shouldered against and overlaps the remnants of a drowned rocky shore with a paleorelief of 4 m that preserves intertidal to shallow subtidal biotas. Extrapolated from the big bed's rock face (1,830 m^2) and the width of the eroded shelf on which it resides (8 m), calculations yield a projected volume of 14,500 m^3. Unique to the island, the big bed is interpreted as a major hurricane deposit that moved sand from an offshore bar in an onshore path. Such an event fits the context of the Pliocene Warm Period, during which global El Niño conditions were more intense than today.

Keywords: Storm surge; NE Atlantic; Azores Islands; El Niño climate; Pliocene Warm Period

1. Introduction

Hurricanes commonly are agents of coastal erosion through scouring of nearshore deposits as a result of powerful storm-tide ebb currents. In contrast, massive onshore transport of sediments by hurricanes appears to be a rare phenomenon that requires exceptional conditions. Circumstances leading to the capture of an enormous sand body transferred from a shelf location and rapidly deposited in a more onshore setting are explored, herein. This letter communicates discovery of a super-hurricane event recorded in Pliocene strata from Santa Maria Island in the Azores archipelago in the NE Atlantic Ocean.

During the Pliocene Warm Period (4.5–3.0 Ma) sea surface temperatures (SST) across the equatorial Pacific Ocean stimulated El Niño conditions more prevalent than today (Brierley et al., 2009); simulations on relaxation of atmospheric circulation suggest that the El Niño effect spread beyond the Pacific to the Atlantic Ocean. Modern El Niño conditions in the Pacific Basin are claimed to influence an increased incidence of hurricanes in the Atlantic (Goldenberg et al., 2001), particularly when coupled with the warm phase of the Atlantic Multidecadal Oscillation. Such an effect was maximized during the Pliocene, when the mean annual SST around Santa Maria ranged from about 3.7 to 6.3°C higher than the present value of 20.6°C (Ávila et al., 2016).

The Azores region is characterized by high storminess, with extreme storm events once every seven years, on average. During the Atlantic hurricane season, several hurricanes reach the Azores, but sometimes reduced to tropical cyclones. Recent hurricanes that impacted the Azores include “Hurricane 15” (1932), Hannah (1959), Jeanne (1998), Gordon (2006 and 2012). Hurricane frequency in the Azores has been on the rise during the last 50 years (Andrade et al., 2008), with arrival of shorter but more extreme events. Verification of Pliocene hurricane deposits from the rock record offers a cautionary outlook as climatologists point to the effects of changing storm intensities related to global-warming trends (Mei et al., 2015).

2. Regional setting

Strata on uplifted volcanic ocean islands offer a unique opportunity to examine past, mid-ocean coastal sedimentary environments and fossil biotas. Santa Maria in the Azores (Fig. 1A) is one such island with extensive, lower Pliocene marine carbonates preserved by volcanic activity and exposed by subsequent uplift and erosion (Ávila et al., 2015; Rebelo et al., 2016; Ramalho et al., 2017). The south shore Malbusca section exhibits a 150-m, volcano-sedimentary sequence containing effusive products inter-bedded with bioclastic-rich sandstone, capped by subaerial lava flows (Fig. 1B). The most continuous sedimentary succession amounts to 20 m and includes a 5-m thick sandstone bed (Fig. 1C-G) distinguished by laminae composed of dark minerals in contrast to lighter carbonate grains (Rebelo et al., 2016). Stratigraphic disconformities frame distinctive sandstone deposits, both below and above.

3. Methodology

A key disconformity beneath the sand body under study was partially excavated to remove weathered sediment and reveal the extent of paleorelief. Fossils attached to the exposed rock surface were identified, and photographed in place. Trace fossils observed in natural exposures were cleaned where necessary. Trace-fossil associations were interpreted as standard ichnofacies indexed to bathymetrical energy zones according to well-established models (Pemberton, 2001; MacEachern et al., 2012).

Description of the principal sand body considered lithology, texture, contact between units, erosional features, and macrofossils. Samples retrieved from major sub-units were subjected to grain morphoscopy to evaluate angularity, sphericity, shape, luster, and corrosion. Observations under a binocular microscope (Leica EZ4; 30x) established grain typology. Fractions (1–3Φ) specifically were chosen for this purpose. Using a count of 100 grains/sample, grains were separated into bioclasts as opposed to lithic and mineroclasts. In a GIS environment (ArcGIS 10.2™), three-dimensional volume estimations of the Malbusca sandy package were calculated using the bed's cross-sectional area. Area in two-dimensions was extended as a function of potential outcrop width to extrapolate minimum sediment volumes.

4. Results

4.1. *Pre-erosional facies*

Basal strata feature rhodolith limestone that fills depressions in pillow basalt with as much as 1.4 m in eroded paleorelief. Succeeding layers include a shell breccia followed by bioturbated volcaniclastic and calcarenite sandstone through a composite thickness of 4–6 m (Rebelo et al., 2016, their table 1). Trace fossils in the overlying sandstone include abundant ray holes (*Piscichnus* isp.), traces attributed to *Bichordites*, among many others (Uchman et al., 2016).

4.2. Sea cliff facies

A disconformity in the succession reveals 4 m of vertical paleorelief eroded in pre-existing strata (see above). The upper 0.80 cm of the excavated surface (Fig. 2A) is widely encrusted by crustose (nongeniculate) coralline red algae referred to the genus *Lithophyllum*. Algal crusts (1 to 2 mm) merge with locally abundant shells (*Spondylus* sp.). The bivalves (3 to 4 cm) are attached to the vertical wall (Fig. 2B). Some hosted encrusting bryozoans, which show that encroachment by crustose red algae in real ecological time was not total. Holes crossing the crustose red algae relate to *Gastrochaenolites* isp. (Fig. 2B, inset) having an affinity to the endolithic bivalve *Myoforceps aristatus*. The borings (up to 2 cm) are oriented in an oblique, downward direction. An average surface area of 10 cm^2 is populated by as many as 17 bivalve borings. The disconformity surface shows cavities and overhangs that include encrustations by polychaete worm tubes (Fig. 2C).

4.3. Sandstone facies

A fully exposed paleocliff is not directly observable beneath the mantle of the big sand bed, but abutting sediments extend eastward from the site of bioencrustations on the excavated disconformity over a distance of 34 m (Fig. 1C), to rest on darker and coarser sands and pebbles (Fig. 1D). The bed's lower part consists of coarse, poorly sorted, massive sandstone with dispersed basaltic pebbles (mostly 1-cm diameters, rarely up to 10 cm) and detritus from bivalve shells and echinoid tests. Coarse sand pinches out in both directions. Grains are finer and the pebbles disappear laterally with pinch-outs. The upper part of the big bed abuts and overlaps the former seacliff (Fig. 1E). Laminae preserved in this part of the sand body are planar and quasi-planar (Fig. 1F), or show small to larger scale hummocky cross-stratification

(Fig. 1G). In particular, there is no evidence for a downward drape in laminae from above.

The top of the big bed is only partially bioturbated. *Thalassinoides* isp. forms boxwork galleries that descend locally up to 1 m (Fig. 1H). Vertical shafts that probably belong to ?*Ophiomorpha* are present in places. Variably oriented *Macaronichnus* occurs in the top 10 cm but also extends deeper around other burrows. Above the big bed, several poorly individualized layers (facies 6 of Rebelo et al., 2016) follow as decimeter-thick, partly or totally bioturbated beds of fine-grained sandstone. Some show planar or quasiplanar lamination (Fig. 2D). This facies features diverse trace fossils (Fig. 2E), including *Thalassinoides* isp., ?*Ophiomorpha* isp., *Macaronichnus* isp., *Bichordites* isp., *Piscichnus* isp. and *Dactyloidites ottoi* (Geinitz, 1849).

4.4. Sand descriptors and size of surviving sand deposit

The big bed exhibits alternating lamina with dark (pyroxene-rich) and white (shell-rich) components. Overall, heavy minerals and bioclasts correspond to more than 98% of the sediment assemblage. The thickness of darker laminae also appears to decrease upwards.

Sediment grain-size in the big bed varies between coarse silt and very-fine to fine sand. These differences, which vary as much as 0.5 Φ between adjacent laminae, result from greater or lesser presence of bioclasts (coarser than darker minerals). Morphoscopic analysis revealed that the darker layers are composed by 50% to 70% rounded to sub-rounded grains (abundant clinopyroxenes and vestigial olivine and plagioclase). The lighter layers still represent approximately 30% of darker (denser) minerals with the balance made up by bioclasts. Analysis also shows that the bioclasts are composed of silty sand-size or larger fragments in fine, sub-angular to angular sand. Mineral grains exhibit a relative maturity (well-rounded and fine) compared to bioclasts.

Based on outcrop photographs of the Malbusca big bed, polygons drawn in ArcGIS allowed for the estimation of volume for the principal sand deposit. A basalt rockfall separates the exposed storm layers into two adjacent areas. The two-dimensional surface area for the combined rock face in the two sections covers 1,830 m^2. The basalt ledge on which the entire Malbusca sedimentary sequence sits, projects seaward from beneath that sequence to form the lip of a plunging coastline. Due to outcrop recession, the original sand deposit retreated approximately 8 m landward from the surviving outer lip of the basalt ledge, implying a minimum accommodation space of >14,500 m^3 formerly occupied by the big bed. The additional volume of sand in an eastward extension blocked by a lava delta (Fig. 1B) remains to be estimated.

5. Discussion

5.1. Bathymetric constraints from confining strata

The trace fossil assemblage from strata that pre-date erosion of the sea cliff is dominated by *Macaronichnus* with *Palaeophycus* and *Ophiomorpha* that belong to the Skolithos ichnofacies and corresponds to depths from the foreshore to middle shoreface (Pemberton et al., 2001). These horizons mark marine flooding events during a general transgression prior to paleoshore erosion.

Strata that bracket the big sand bed at Malbusca somewhat constrain the absolute minimum water depth at the time of the hurricane event. The sea cliff encrusted extensively by coralline red algae and to a lesser degree by bivalves and polychaete worm tubes (Fig. 2B, C) marks a distinct disconformity. Formed by lime-rich sandstone, the cliff also was bored by endolithic bivalves (*Myoforceps aristatus*) that indicate intertidal to very shallow-water conditions.

The subsequent storm bed incorporates the trace fossils *Thalassinoides*, ?*Ophiomorpha* and *Macaronichnus* present at the top and disappearing downward that collectively show colonization from above of rapidly deposited sediment (Fig. 1H). *Ophiomorpha* is typical of the *Skolithos* ichnofacies, but may occur in storm beds within the *Cruziana* ichnofacies in which *Thalassinoides* is common. Because dispersed *Macaronichnus* also may occur in the shoreface (Bromley et al., 2009), the trace fossil assemblage at the top of the hurricane event bed probably refers to a transition between the *Skolithos* and the *Cruziana* ichnofacies, somewhere near fair-weather wave base.

The more diverse trace fossil assemblage from the thinner, overlying storm beds (facies 6 of Rebelo et al., 2016) is typical of the proximal-archetypal *Cruziana* ichnofacies, which extends from the lower shoreface to the upper offshore. Water depth fluctuated probably near fair-weather wave base or slightly deeper, because *Dactyloidites ottoi* from this assemblage is typical of the “lower *Skolithos* and upper *Cruziana* ichnofacies” in food-rich siliciclastic sediments (Wilmsen and Niebhur, 2013).

5.2. Paleostorm analysis

Based mainly on Holocene deposits, paleostorm analysis is a growing field of study (Nott, 2004). This work typically relies on a multi-proxy approach (e.g.

stratigraphical, grain-size, geomorphological, and micropaleontological criteria) in order to unequivocally identify storm events in the geological record. Among key features, recognition of massive and laminated sequences often is used as a key identifier (Switzer and Jones, 2008).

The unusually thick (5 m), finely laminated sands at Malbusca may be traced farther eastward for approximately 200 m across inaccessible coastal bluffs (Fig. 1B). Capping the Malbusca laminated bed, is a strongly bioturbated bioclastic sandstone featuring ichnofacies common below fair-weather wave base (Uchman et al., 2016). In turn, this sequence is overlain by volanic submarine sheet flows with basal peperites; their thickness denotes a minimum paleowater depth of 20 m. A comparable paleodepth is registered by the height of a lava delta located laterally east of the Malbusca section (Fig. 1B), the toe of which is level with an extension of the big sand bed.

Composition of the Malbusca big sand bed points to deposition from a major event capable of transporting sediments within the upper flow regime. This is further supported by a massive, poorly-sorted and coarser sandy basal unit and by the upward increase in carbonate grains within the upper laminated unit (see division in Fig. 1C). This gradation reflects different flow conditions from a turbulent phase to a suspension grading phase. The first indicates non-uniform flow with spatial deceleration resulting in bed-load deposition. Conversely, the second phase denotes almost a normal grading sequence with upward grain-size decrease and increase in lighter carbonate components. The overall package implies high-energy flows sustainable only in a single, short-lived event with a very high and continuous aggradation rate. Considering the overall thickness of the big bed, its volume, and its composition, the most likely generating mechanism is an exceptionally intense hurricane event. Grain-size and morphoscopic characteristics of constituent dark minerals also suggest a long-term process responsible for their rounded shape and fine size prior to rapid burial. Overall maturity of the darker mineral grains indicates they were sourced from a more offshore region, likely a submerged sand bar.

Preservation of the Malbusca deposit, combined with its sedimentological characteristics and subsequent superficial reworking by lesser storm events, also implies deposition above storm wave base, which in the Azores today is below about -50 m. The minimum paleo-water depth implied by the volcanic submarine cover (ca. -20 to -25 m) corroborates this inference. Moreover, observations by Meireles et al. (2013) on Pliocene deposits at nearby Ponta do Castelo also report significant sediment transport by storms down to depths of -55 m.

5.3. Conceptual model

Pliocene geomorphology on the south side of Santa Maria Island entailed accommodation space possibly influenced by a shallow trough-shaped depression at the side of an inshore submarine ledge. This space favored effective sediment selection (alternation of lighter and denser laminated beds) to capture the sudden transfer of sediments from an outer sand bar. A conceptual model (Fig. 3A, B) depicts physical relationships at Malbusca prior to development of the upper volcanic units (Ramalho et al., 2017) when the island was much like today's platform around the razed volcanic edifice of Lord Howe Island in the Tasman Sea (Kennedy et al., 2011). Lateral to the submarine ledge down to the east is a lava delta (Figs. 1B, 3) that blocked the oncoming sand wave from a SE to NW directed storm surge. The height of the lava delta places constraints on water depth at the time of the storm, which is in agreement with the thickness of the submarine volcanic sequence (~20 to 25 m) that overlies the Malbusca sedimentary package.

Due to difficulties inherent with limited outcrop access, use of light and portable equipment is necessary for ongoing studies. Future work will include application of high-resolution analysis using magnetic susceptibility, geochemical analysis (XRF), digital grain-size analysis, and numerical modeling (e.g. Delft 3D coupling hydro and sediment transport mechanisms) in order to more clearly elucidate the depositional conditions of the storm event.

6. Conclusions

The Malbusca section on Santa Maria Island is notable for two features captured in ecological time and preserved in the context of events more often condensed by the passage of geologic time. The first is a plunging rocky shore with a minimum relief of 4 m, the upper part of which retains encrusting fossils characteristic of an inter-tidal to shallow subtidal setting. Directly associated with the paleoshore as a physical abutment, the second feature is attributed to a 5 m-thick hurricane deposit succeeded by lesser storm beds. Under hurricane action, the accommodation space necessary to receive and retain (in part) the first big sand bed may have been a trough-shaped depression along the edge of a submerged, former rocky shore. An uneven surface at the top of the big bed hints that some sand may have undergone seaward backwash prior to the arrival of subsequent but smaller storm beds. Trace fossil suites indicative of the *Skolithos* ichnofacies are poorly represented in the upper part of the principal storm bed, but are more extensive in the amalgamation of subsequent storm beds. The bathymetry of the *Cruziana* ichnofacies in these later storm beds suggests a regime below fair-weather wave base but above normal storm base. In turn, these sediments were conformably overlain by massive submarine lava sheet flows that formed thick layers in no less than 20 m of water to protect the surviving package of storm sands from further erosion. Overall, the profile of the Malbusca big sand bed draws a tangible connection with the pattern of surface-water temperatures and atmospheric conditions projected for the Pliocene Warm Period (Brierley et al., 2009), as factors promoting intense hurricanes.

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Figure Captions

Fig. 1. Location and appearance of the thickest storm bed (bb – big bed); other abbreviations: abb – sediments above the big bed; ba – basalts, cl – fossil cliff; ld – lava delta; ubb1, ubb2 – sediment beds below the big bed; *Ma – Macaronichnus* isp., *Th – Thalassinoides* isp. Boundaries are marked by dashed lines. A. Location map showing contours of the island and its shelf; B. General view of the section located between volcanic rocks; C. General view of the big bed; D. Base of the big bed and the underlying sediment; E. Incision of the big bed in the underlying sediment and the fossil cliff; F, G. Laminae in the big bed; H. Top of the big bed bioturbated with *Macaronichnus* and *Thalassinoides*.

Fig. 2. Details from stratigraphic units below and above the thickest storm bed. Abbreviations as in Fig. 1, moreover: ac – algal crust; cb – crustacean burrow; e – echinoid, *Clypeaster altus* (Leske, 1778; *Bi – Bichordites* isp., *Do – Dactyloidites ottoi* (Geinitz, 1849), *En – Entobia* isp., *Ga – Gastrochaenolites* isp., Pi – *Piscichnus* isp.; A. The fossil cliff excavated from the big bed; B. Face of the fossil cliff showing borings in the sandstone and a *Spondylus* shell. Insert shows *Gastrochaenolites*, the

entrance to which is covered by algal crust; C. Face of the fossil cliff showing bivalve borings and encrusting worm tubes; D, E. Planar or quasiplanar lamination in storm beds overlying the big sand bed with diverse trace fossils (as labeled).

Fig. 3. Model showing a hypothetical sand bar as the source for the big bed: A. Before the storm event; B. After the storm event moved sand shoreward against a rock ledge represented by a submerged paleoshore.

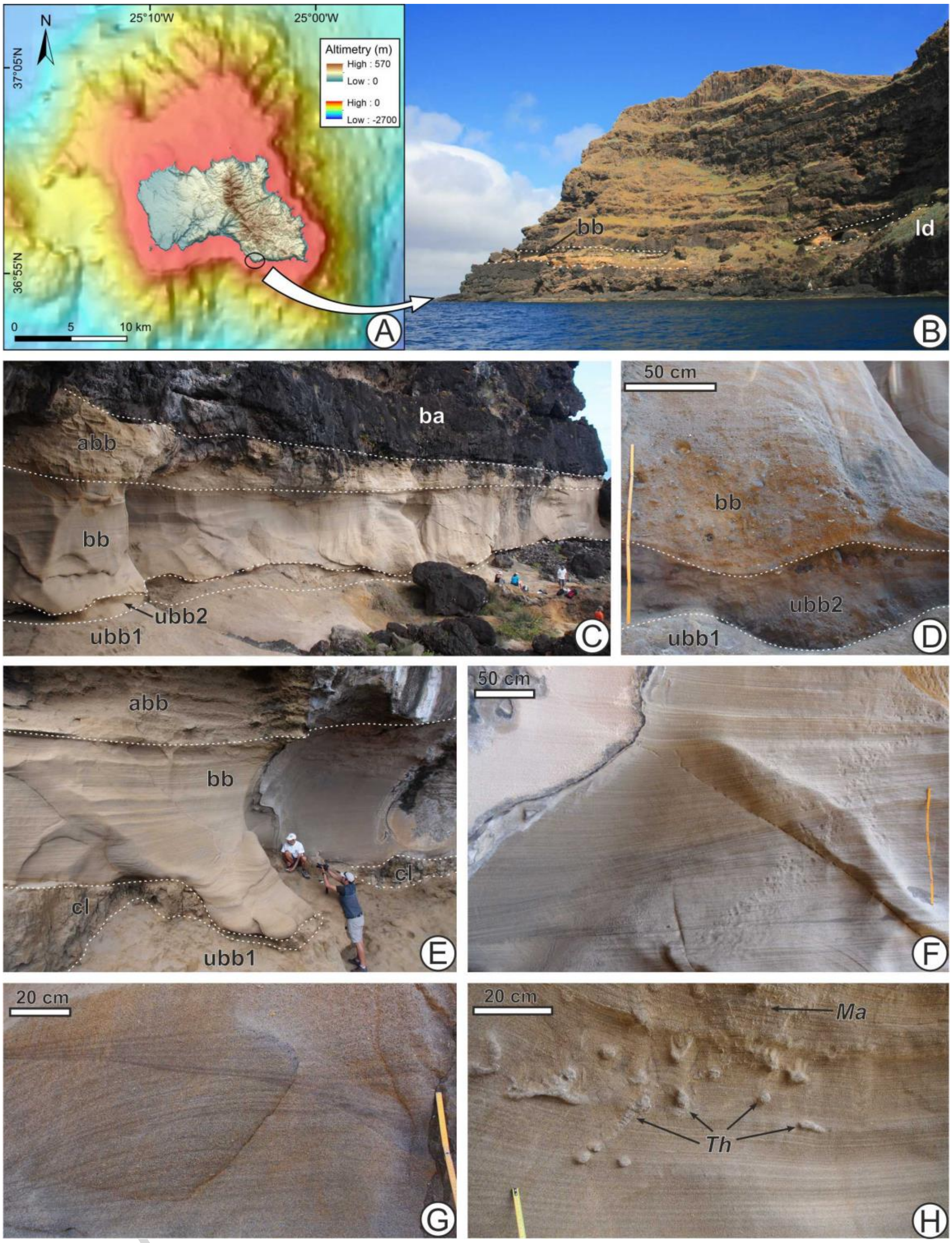

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Fig. 1

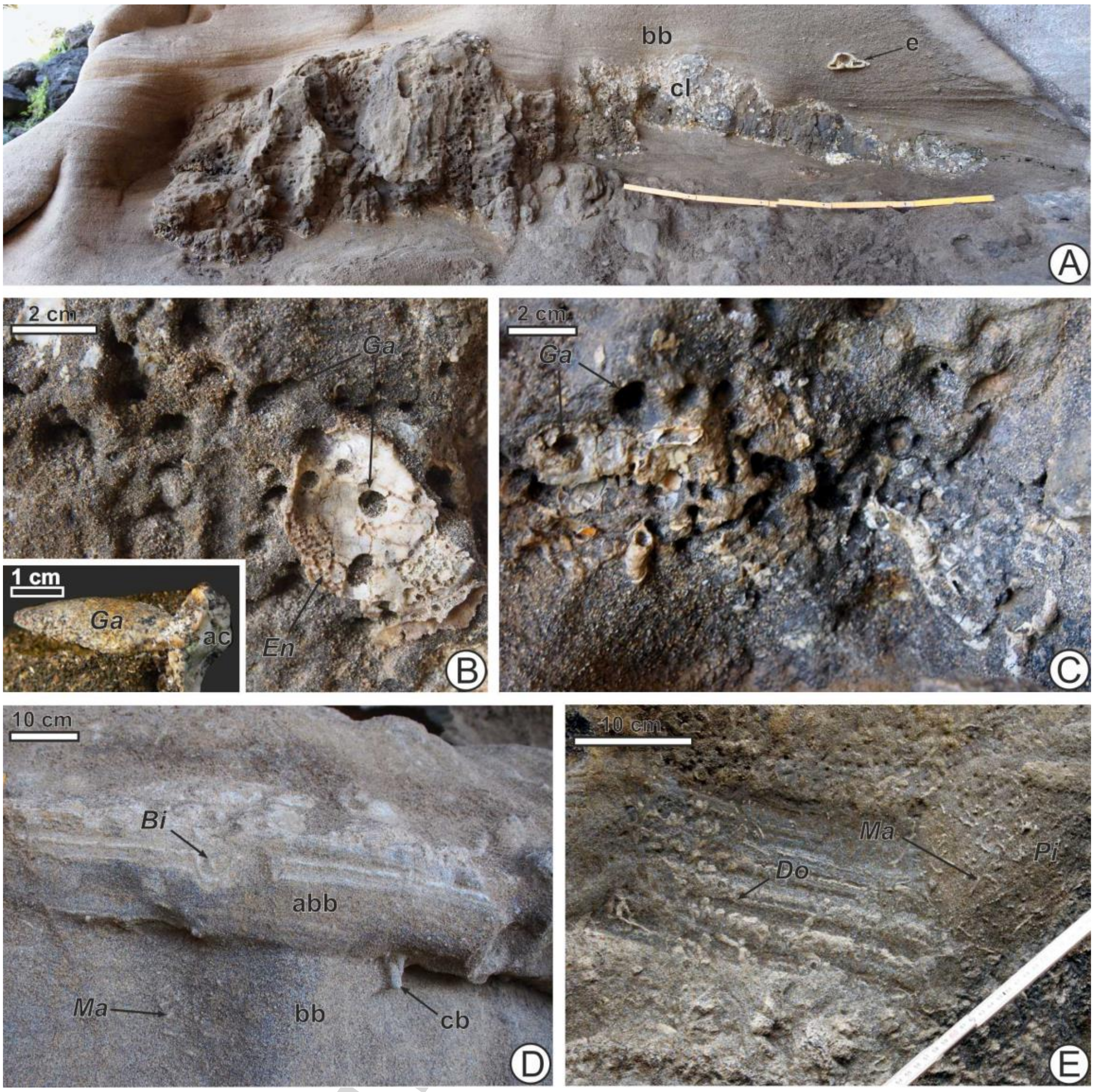
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Fig. 2

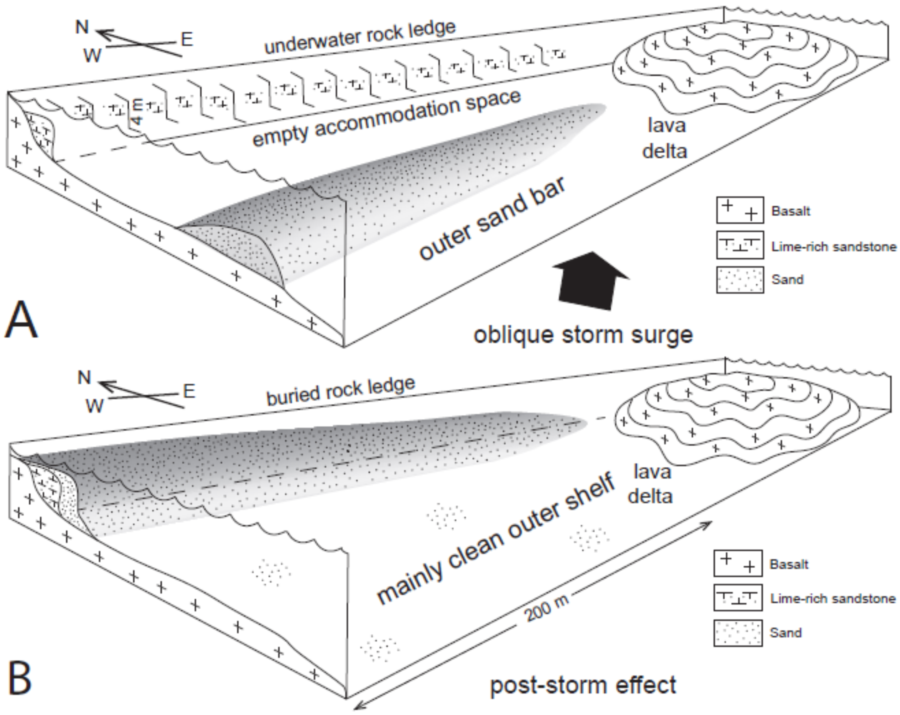

Fig. 3

Highlights

- Tangible evidence given for massive hurricane deposit on an oceanic island.
- Age of the deposit correlates with Pliocene Warm Period & El Niño climate.
- Thickness, lateral extent, and volume of the deposit are calculated.
- Sedimentological features supporting major storm event are summarized.
- Bathymetric relationships checked through trace-fossil analysis.